

Eddy Resolving Global Ocean Prediction including Tides

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<http://www.hycom.org>

<http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html>

<http://www7320.nrlssc.navy.mil/hycomARC>

LONG-TERM GOALS

Use the HYbrid Coordinate Ocean Model (HYCOM) with tides, dynamic sea ice, and data assimilation in an eddy-resolving, fully global ocean prediction system with $1/25^\circ$ horizontal resolution that will run in real time at the Naval Oceanographic Office (NAVOCEANO) starting in 2012. The model will include shallow water and provide boundary conditions to finer resolution coastal models that may use HYCOM or a different model.

OBJECTIVES

To develop, evaluate, and investigate the dynamics of $1/25^\circ$ global HYCOM (HYbrid Coordinate Ocean Model) with tides coupled to CICE (Los Alamos Community Ice Code) with atmospheric forcing only, with data assimilation via NCODA (NRL Coupled Ocean Data Assimilation), and in forecast mode. Also to incorporate advances in dynamics and physics from the science community into the HYCOM established and maintained within the Navy.

APPROACH

Traditional ocean models use a single coordinate type to represent the vertical, but no single approach is optimal for the global ocean. Isopycnal (density tracking) layers are best in the deep stratified ocean, pressure levels (nearly fixed depths) provide high vertical resolution in the mixed layer, and σ -levels (terrain-following) are often the best choice in coastal regions. The generalized vertical coordinate in HYCOM allows a combination of all three types (and others), and it dynamically chooses the optimal distribution at every time step via the layered continuity equation. HYCOM uses a C-grid, has scalable, portable computer codes that run efficiently on available DoD High Performance Computing (HPC) platforms, and has a data assimilation capability.

Global HYCOM with $1/12^\circ$ horizontal resolution at the equator (~ 7 km at mid-latitudes) is the ocean model component of the eddy-resolving nowcast/forecast system currently running in real time and undergoing its OPTEST on the Cray XT5 at the Naval Oceanographic Office (NAVOCEANO). It provides nowcasts and forecasts of the three dimensional global ocean environment. See <http://www7320.nrlssc.navy.mil/GLBhycom1-12/skill.html> for movies, snapshots and comparisons to

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observations and <http://www.hycom.org> for model fields. HYCOM is coupled to the Los Alamos Community Ice CodE (CICE) (Hunke and Lipscomb, 2004) via the Earth System Modeling Framework (ESMF) (Hill et al., 2004), although currently for Arctic-only configurations. Coupling between the ocean and sea ice models more properly accounts for the momentum, heat and salt fluxes at the ocean/ice interface. The final component of the nowcast/forecast system is the NRL Coupled Ocean Data Assimilation (NCODA) which is a multivariate optimal interpolation scheme that assimilates surface observations from satellites, including altimeter and Multi-Channel Sea Surface Temperature (MCSST) data, sea ice concentration and also profile data such as XBTs (expendable bathythermographs), CTDs (conductivity temperature depth) and ARGO floats (Cummings, 2005). By combining these observations via data assimilation and using the dynamical interpolation skill of the model, the three dimensional ocean state can be accurately nowcast and forecast.

The principal goal of this project is to perform the necessary R&D to prepare to provide a next-generation ocean nowcast/forecast system with real time depiction of the three-dimensional global ocean state at fine resolution (1/25° on the equator, 3.5 km at mid-latitudes, and 2 km in the Arctic). A major sub-goal of this effort is to test new capabilities in the existing 1/12° global HYCOM nowcast/forecast system and to transition some of these capabilities to NAVOCEANO in the 1/12° system, and others in the 1/25° global system. The new capabilities support (1) increased nowcast and forecast skill, the latter out to 30 days in many deep water regions, including regions of high Navy interest such as the Western Pacific and the Arabian Sea/Gulf of Oman, (2) boundary conditions for coastal models in very shallow, and (3) external and internal tides, the latter will initially be tested at 1/12°, to minimize computational cost, but will transition to NAVOCEANO only in the 1/25° system because at this resolution it will replace regional models with tides (all these will greatly benefit from the increase to 1/25° resolution). In addition to the NRL core tasking covered here, this effort will collaborate with a core team of similar size at FSU COAPS, with other parties interested in HYCOM development, and ONR field programs to test and validate the model in different regions and different regimes. Demonstrated advancements in HYCOM numerics and physics from all sources will be incorporated through this project.

WORK COMPLETED

The first 1/25° global HYCOM simulations (3.5 km resolution at mid-latitudes) were run two years ago with climatological 6-hourly atmospheric forcing. Last year we extended the simulation for 2003-2010 with 3-hourly NOGAPS atmospheric forcing, but still without data assimilation. For comparison, a near twin 1/12° global HYCOM simulations was also integrated 2003-2010 with the same NOGAPS forcing.

We ran the very first eddy resolving (1/12°) 3-D global ocean simulation with standard atmospheric forcing and tides in FY08 (Arbic et. al., 2010). Last year we performed a second multi-year simulation with an improved bottom tidal drag field, which was an exact twin of the 2003-2010 NOGAPS forced case mentioned above. This year, the results of these new simulations have been extensively analyzed and are the subject of multiple papers submitted this year.

There have been several improvements to how we handle tides this year: (a) a new bottom drag field based on bottom roughness from the 30" GEBCO_08 bathymetry, (b) a 48-hour filter on near-bottom currents, for tidal bottom drag, that stops all semi-diurnal tides but passes 70% of diurnal tides, and (c) a spatially varying "scalar" approximation to self-attraction and loading. In addition new 1/12° and

1/25° bathymetries have been produced, also based on 30" GEBCO_08. With these improvements in hand, we have started our 3rd global 1/12° simulation with NOGAPS and tides and the very first such global simulation at 1/25°.

Adding assimilation to 1/25° global HYCOM has been difficult because it is running on a three year old Cray XT5 which has too little memory per node to run NCODA at this resolution. This is the case even if NCODA's capability to perform the analysis on a coarser grid is used. So we are instead downscaling to a 3x coarser grid before invoking NCODA and up-scaling to the original grid after NCODA. All the software needed for this is now in place, but we are not yet routinely running 1/25° global with data assimilation. We have also demonstrated, with the 1/12° global system, that using HYCOM daily means as the first guess for NCODA is an effective way to allow for tides in our existing data assimilative system and that including the daily solar cycle and First Guess at Appropriate Time (FGAT) for SST improves the nowcast.

The Arctic Cap Nowcast/Forecast System (ACNFS) consists of the subset of our tri-pole 1/12° global HYCOM domain that is north of 40°N (3.5 km resolution near the North Pole, 6.5 km at 40°N) coupled to the Los Alamos Community Ice Code (CICE) via the Earth System Modeling Framework (ESMF) with NCODA 3DVAR data assimilation of ocean state and sea ice concentration. It has run in hindcast mode from July 2007 and in real time since June 2010. It is undergoing its OPTEST on the IBM POWER6 at NAVOCEANO. See <http://www7320.nrlssc.navy.mil/hycomARC> for movies, snapshots and comparisons to the NIC frontal analysis.

RESULTS

Currently, ice concentration data is assimilated into ACNFS from real-time SSM/I at a resolution of approximately 25 km. Since the resolution of ACNFS is approximately 3.5 km, higher resolution sea ice information from satellites is critically needed as model grid resolutions increase in sea ice forecast systems. Starting in summer of 2010, satellite derived 12.5 km ice concentration from AMSR-E was made available for use in real-time. In order to compare the effect of higher resolution satellite data in ACNFS, a one year hindcasts with assimilation of ice concentration fields from SSM/I and AMSR-E were conducted.

The first test was run using assimilation of all available oceanic data and SSM/I derived ice concentration fields via NCODA into the system. The SSM/I concentration field is derived using the Navy's CAL-Val algorithm (Hollinger, 1991). The data is available in near real-time via NAVOCEANO. This simulation was integrated using NOGAPS forcing over the one year period 01 July 2009 – 30 June 2010. The second test was run exactly the same as the first test except AMSR-E derived ice concentration fields were assimilated via NCODA into the system instead of SSM/I ice concentration. The AMSR-E concentration field is derived using NASA Team 2 algorithm (Markus and Cavalieri, 2000), and is made available in near real-time from the NASA Land Atmosphere Near real-time Capability for EOS (LANCE) website (<http://lance.nasa.gov>).

For this study the mean distance between the independent, daily observed National Ice Center (NIC) ice edge and the ACNFS hindcasts was calculated (Table 1). Model ice edge locations are defined as those grid points that exceed a threshold value of 5% ice concentration. Daily means are calculated from the distances between each NIC observed point and the nearest model-derived ice edge location. These daily means were calculated for the full Arctic and six regional seas: Greenland Sea, Barents

Sea, Laptev Sea, Sea of Okhotsk, Bering/Chukchi/Beaufort Seas and the Canadian Archipelago. Figure 1 shows a time series plot of daily mean distances between the independent NIC and the model's ice edge for the Bering/Chukchi/Beaufort Seas region.

Table 1: Mean distances (km) between the independent NIC ice edge and the ACNFS assimilating AMSR-E or SSM/I. Bold numbers indicate column with lowest mean distance.

Region	ACNFS assimilating AMSR-E	ACNFS assimilating SSM/I	% Improvement
Full Arctic	18.1	21.6	16%
Greenland	39.6	35.7	-9%
Barents	34.9	39.3	11%
Laptev	64.7	64.4	0%
Sea of Okhotsk	48.2	62.8	23%
Bering/Chukchi/Beaufort Seas	46.5	58.7	21%
Canadian Archipelago	53.8	48.1	-11%
Average	43.7	47.2	7%

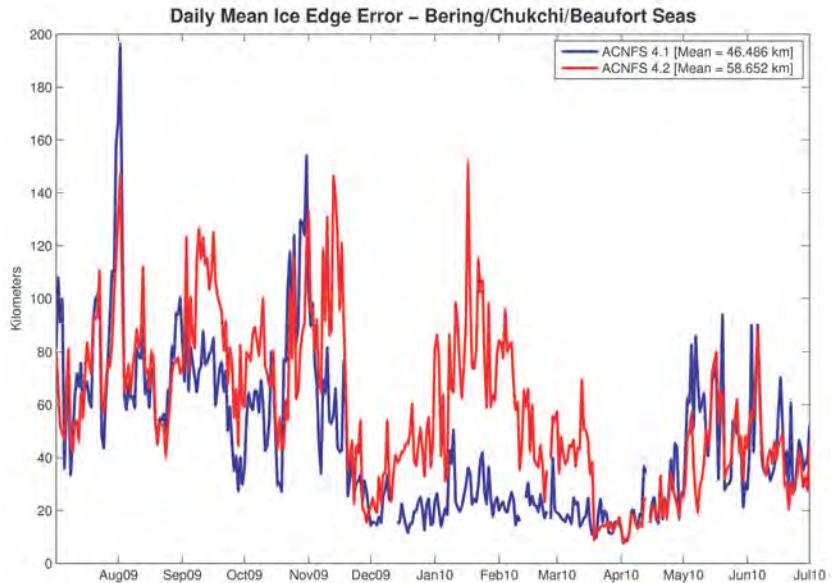


Figure 1. Daily mean distances (km) from the NIC observed ice edge locations to the edge locations from ACNFS assimilating AMSR-E (blue) and SSM/I (red) for the Bering/Chukchi/Beaufort Seas region from July 2009 – June 2010.

For the full Arctic region, the mean distance between the ice edge from ACNFS assimilating AMSR-E ice and the NIC ice edge was 18.1 km, compared to 21.6 km for the ACNFS with SSM/I ice concentration assimilation. This represents a 16% improvement. While overall improvement was made assimilating AMSR-E ice concentration, it is noted that not all areas showed improvement. In particular, ACNFS with SSM/I data assimilation showed better performance in two areas: Greenland and the Canadian Archipelago. Further investigation into each satellite data in these two regions is required to understand the difference in model response. The OPTEST of ACNFS is proceeding with SSM/I, but we plan to switch to AMSR-E should ACNFS successfully pass its OPTEST.

Figure 2 displays the amplitude of the M_2 signature in both altimeter data (top panel; Ray and Mitchum 1996, 1997; Ray and Byrne 2010) and our second multi-year HYCOM simulation (bottom panel). HYCOM is capturing the hotspots of internal tide generation well, its RMS amplitudes are within about 20% of those in altimeter data for the most important constituents in these areas. Brian Arbic's FY11 ONR report for the related project *“Insertion, validation, and application of barotropic and baroclinic tides in 1/12 and 1/25 degree global HYCOM”* contains several more results from this simulation.

We studied three global HYCOM model experiments differing only in horizontal resolution and data assimilation forced with three-hourly, 0.5° NOGAPS atmospheric fields. The models are a $1/12^\circ$ (~ 9 km at the equator) and a $1/25^\circ$ (~ 4.4 km at the equator) horizontal resolution non-assimilative models, denoted respectively as $1/12^\circ$ FR and $1/25^\circ$ FR and a $1/12^\circ$ with data assimilation, denoted as $1/12^\circ$ DA. The initial conditions for each experiment is spin-up from rest using the GDEM3 climatology for 10 years using climatological forcing. Thereafter, the model is forced with interannually varying NOGAPS atmospheric fields from 2003 to 2009. For the non-assimilative models, the analysis is performed for the five years 2005 to 2009. Only the two years, 2008-2009, are examined for the data-assimilative, where observations of satellite derived sea surface height (SSH) and vertical profiles of temperature are incrementally inserted using a MultiVariate Optimal Interpolation scheme (Cummings, 2005).

The modeled kinetic energy is compared to three independent sets of observations from satellite altimetry (150 m) (Ducet *et al.*, 2000), ARGO floats at 1000 m (Lebedev *et al.*, 2007), and deep current moorings (Scott *et al.*, 2010).

In Figure 3, the EKE of the models at 150 m is compared with geostrophic velocity estimates from mapped satellite altimeter sea surface heights (SSH) (Ducet *et al.*, 2000). At 150 m, which is below the wind-driven mixed layer, but still representative of the upper ocean, the EKE of the $1/25^\circ$ FR is the highest at $181 \text{ cm}^2 \text{ s}^{-2}$ exceeding the altimeter estimate by 14%. Both $1/12^\circ$ FR and $1/12^\circ$ DA have nearly the same EKE ($122 \text{ cm}^2 \text{ s}^{-2}$) approximately 23% below the altimeter estimate ($159 \text{ cm}^2 \text{ s}^{-2}$). The $1/12^\circ$ models rapidly attenuate the EKE with depth which makes a quantitative comparison with the surface geostrophic velocity difficult. Among the models, $1/12^\circ$ DA is highly correlated with the altimeter EKE with a correlation coefficient of 0.79. We expect the energy estimates from the SSH are affected by sampling artifacts. The mapped geostrophic velocity estimates will be lower than the true geostrophic velocity due to the removal of variability on times shorter than approximately 10 days and horizontal scales smaller than approximately 50 km.

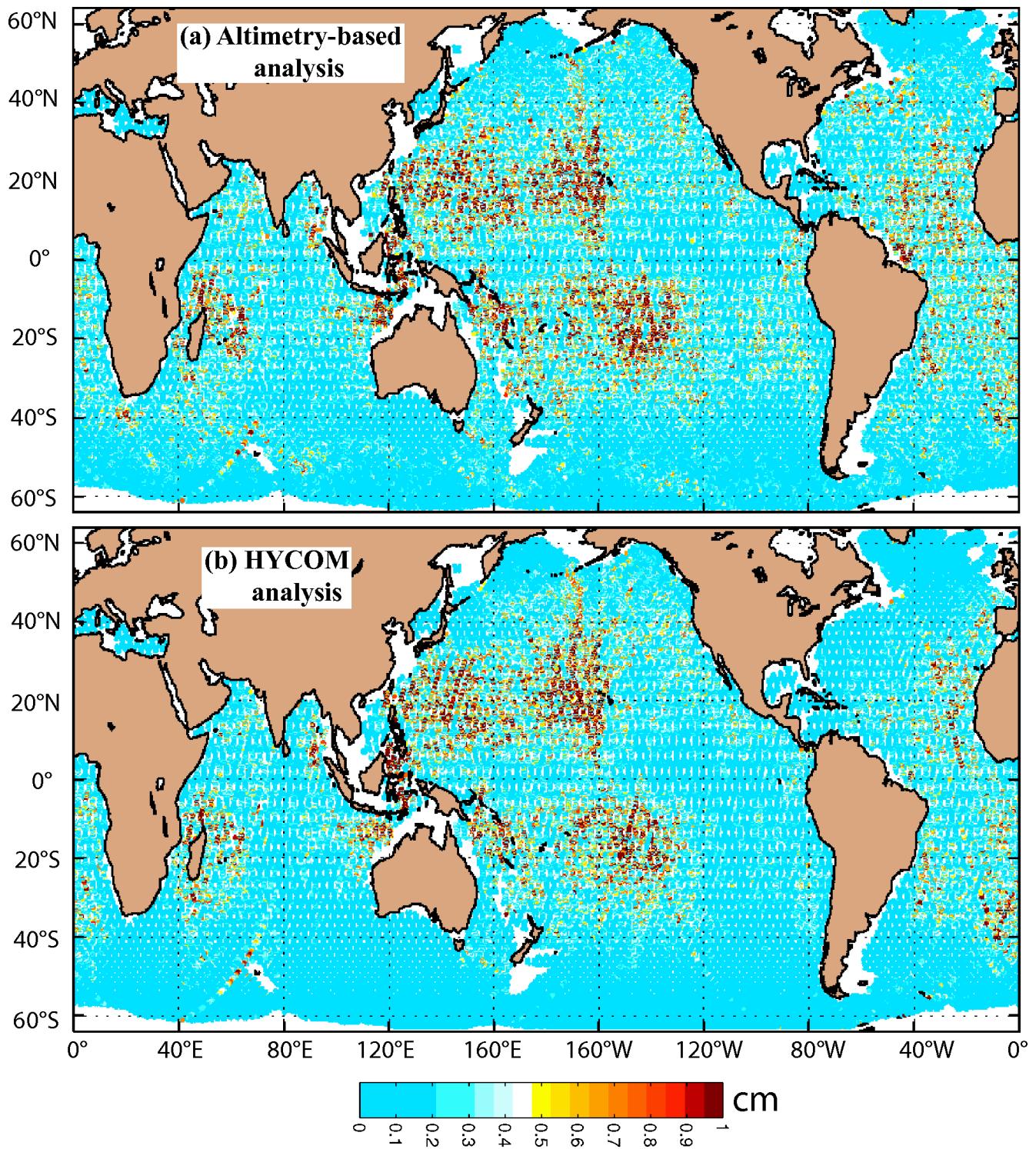


Figure 2. Amplitude (cm) of M_2 internal tide signature in sea surface height, obtained from high-passing the M_2 amplitudes of the full sea surface height. Upper panel: results from satellite altimeter. Lower panel: results from HYCOM.

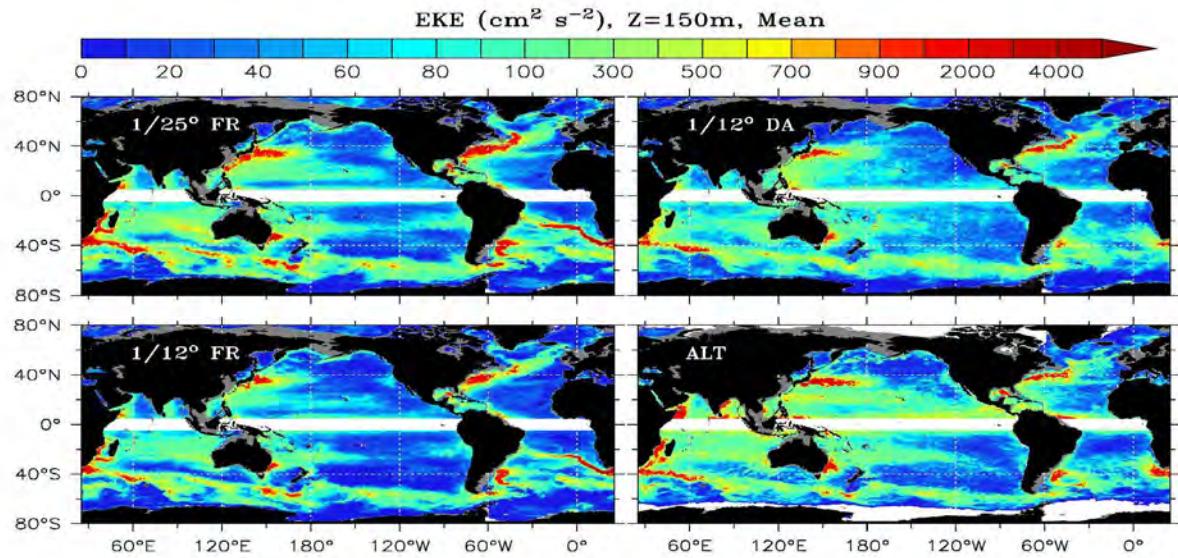


Figure 3 Eddy kinetic energy (EKE in $\text{cm}^2 \text{ s}^{-2}$) at 150m from the three numerical experiments (a) $1/25^\circ$ FR (2005-2009), (b) $1/12^\circ$ DA (2008- 2009), and (c) $1/12^\circ$ FR (2005-2009) and (d) geostrophic velocity estimates from AVISO sea surface height maps for the period 2005-2009. The band 5°N to 5°S is excluded from the EKE estimates.

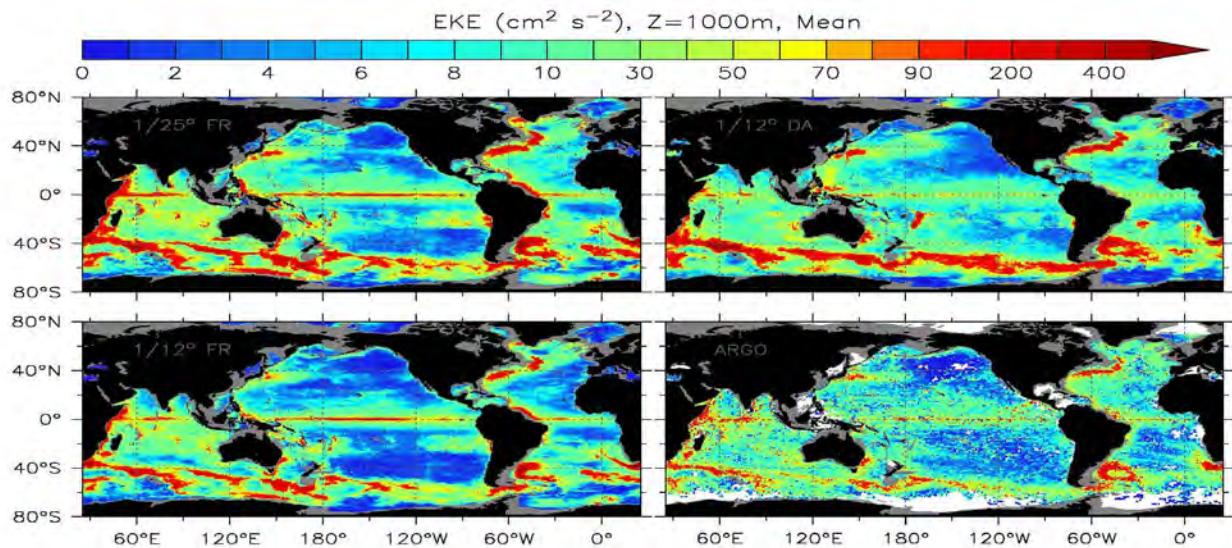


Figure 4. Eddy kinetic energy (EKE in $\text{cm}^2 \text{ s}^{-2}$) at 1000m from the three numerical experiments (a) $1/25^\circ$ FR (2005-2009), (b) $1/12^\circ$ DA (2008-2009), and (c) $1/12^\circ$ FR (2005-2009) and (d) ARGO 1000m drift observations encompassing the period 1998-2009. The surface drift observations are binned into $3^\circ \times 3^\circ$ grids using daily values and only those grid points with at least 100 observations are considered.

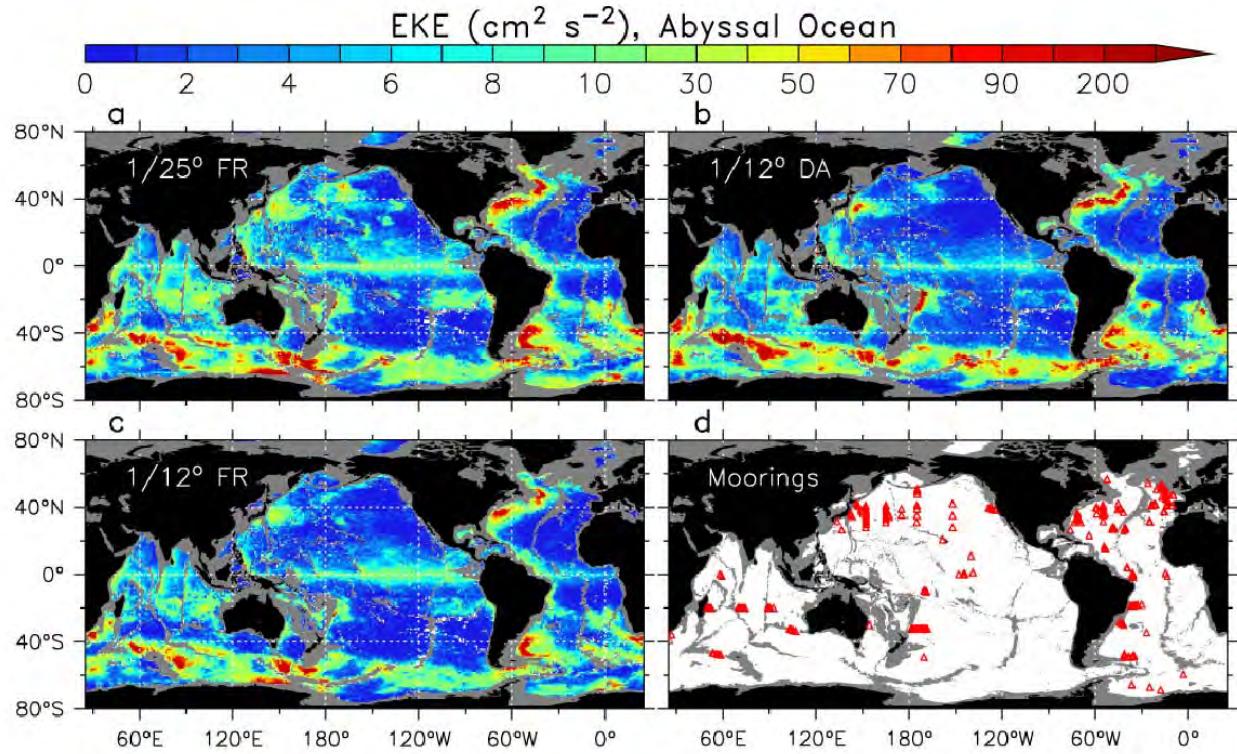


Figure 5. Abyssal ocean EKE ($\text{cm}^2 \text{ s}^{-2}$) averaged below 3000 m from the three numerical experiments (a) $1/25^\circ$ FR, (b) $1/12^\circ$ DA, (c) $1/12^\circ$ FR and (d) locations of the 712 deep current meter moorings used to validate the model kinetic energy (see Scott et al., for details). Moorings with a record at least 180 days are considered. Depths less than 3000 m are masked grey.

Within the lower thermocline we use subsurface drift vectors at 1000 m from the ARGO floats (Lebedev et al., 2007) to examine the EKE. Again, the energy estimates from the ARGO float are subjected to sampling errors. The number of ARGO floats is much smaller than the number of surface drifters. For the past 5 years, approximately 3000 ARGO floats return a position observation every 10 days. Thus, the sampling of the ARGO floats is coarser in space and time with a shorter history than surface drifters. We have binned the drift vectors on a $3^\circ \times 3^\circ$ grid to get at least 100 observations in each grid box. Given the small sample size, we expect the ARGO EKE estimates to be biased low. At 1000 m, the higher resolution and data assimilative model EKE exceed the $1/12^\circ$ FR by 44% (26.4 to $37.9 \text{ cm}^2 \text{ s}^{-2}$) and 28% (26.4 to $33.7 \text{ cm}^2 \text{ s}^{-2}$) respectively. The $1/12^\circ$ FR underestimates the observed EKE by 4%.

Eddies in the upper ocean have a significant impact on the abyssal circulation (depths greater than 3000 m), as abyssal currents can be generated by baroclinically unstable flows via vertical transfer of eddy energy into the abyssal ocean. In the models, high abyssal ocean EKE ($80\text{--}300 \text{ cm}^2 \text{ s}^{-2}$) is confined to the regions below high surface EKE such as western boundary currents and the ACC (Figure 2), a strong indicator of vertical transfer of EKE from the surface to the abyssal ocean. For the global abyssal ocean, the EKE increases by 51% from $8.4 \text{ cm}^2 \text{ s}^{-2}$ to $12.6 \text{ cm}^2 \text{ s}^{-2}$ when the resolution is doubled and by 46% to $12.2 \text{ cm}^2 \text{ s}^{-2}$ with data assimilation. In the $1/12^\circ$ DA, the surface eddies

introduced by the assimilation of sea surface height are driving a stronger eddy-driven abyssal circulation. The SSH anomalies are converted into synthetic profiles of temperature and salinity in the upper ocean for assimilation. A comparison of model EKE with a global dataset of 712 quality controlled moored current meter records (*Scott et al.*, 2010) indicates that the 1/25° FR has the most realistic representation of abyssal ocean EKE and the 1/12° FR underestimates the EKE by 24%. At these locations, the EKE increased from $13.3 \text{ cm}^2 \text{ s}^{-2}$ in 1/12° FR to $18.5 \text{ cm}^2 \text{ s}^{-2}$ in the 1/25° FR, comparable with the observed current meter measurements ($17.5 \text{ cm}^2 \text{ s}^{-2}$). When correlated with the current meter observations, both 1/25° FR and 1/12° DA EKE have higher correlation (~0.8) compared to 1/12° FR (0.71). For the mean global abyssal circulation, the KEM increases by 58% for 1/25° FR and 24% with data assimilation. However, at the current meter locations the KEM increases by 25% with the doubled resolution, but remains virtually unchanged with data assimilation.

IMPACT/APPLICATIONS

The 1/25° (3.5 km mid-latitude) resolution is the highest so far for a global ocean model with high vertical resolution. A global ocean prediction system, based on 1/25° global HYCOM with tides, is planned for real-time operation starting in 2012. At this resolution, a global ocean prediction system can directly provide boundary conditions to nested relocatable models with ~1 km resolution anywhere in the world, a goal for operational ocean prediction at NAVOCEANO. Internal tides and other internal waves can have a large impact on acoustic propagation and transmission loss (Chin-Bing et al., 2003, Warn-Varnas et al., 2003, 2007), which in turn significantly impacts Navy anti-submarine warfare and surveillance capabilities. At present, regional and coastal models often include tidal forcing but internal tides are not included in their open boundary conditions. By including tidal forcing and assimilation in a fully 3-D global ocean model we will provide an internal tide capability everywhere, and allow nested models to include internal tides at their open boundaries.

TRANSITIONS

Both the Global Ocean Forecast System (GOFS) 3.0 and the Arctic Cap Nowcast/Forecast System (ACNFS) have entered OPTEST at NAVOCEANO.

RELATED PROJECTS

There are two related ONR funded projects, one at FSU COAPS under Eric Chassignet and the other at U. Michigan under Brian Arbic. Partnering projects at NRL include 6.1 Global Remote Littoral Forcing via Deep Water Pathways, 6.1 Ageostrophic Vorticity Dynamics of the Ocean and its Impact on Frontogenesis, 6.1 Impact of Spice on Ocean Circulation, 6.2 Full Column Mixing for Numerical Ocean Models, 6.4 Large Scale Ocean Modeling, 6.4 In-situ Guidance, 6.4 Ocean Data Assimilation, and 6.4 Ice Modeling Assimilation from NPOESS. The computational effort is strongly supported by DoD HPC Challenge and NRL non-challenge grants of computer time. In FY11 all 1/25° and some 1/12° global HYCOM cases ran under a FY09-11 DoD HPC Challenge grant.

REFERENCES

Arbic, B.K., A.J. Wallcraft and E.J. Metzger, 2010: Concurrent simulation of the eddying general circulation and tides in a global ocean model. *Ocean Modelling*, 32, 175-187.

Chin-Bing, S.A., A. Warn-Varnas, D.B. King, K.G. Lamb, M. Teixeira, and J.A. Hawkins, 2003: Analysis of coupled oceanographic and acoustic soliton simulations in the Yellow Sea: a search for soliton-induced resonances. *Mathematics and Computers in Simulation*, 62, 11-20.

Cummings, J.A., 2005. Operational multivariate ocean data assimilation. *Quart. J. Royal Met. Soc.*, 131 (613), 3583-3604.

Ducet, N., P. -Y. Le Traon, and G. Reverdin (2000), Global high resolution mapping of ocean circulation from TOPEX/Poseidon and ERS-1 and 2, *J. Geophys. Res.*, 105, 19477-19498.

Hill C., C. DeLuca, V. Balaji, M. Suarez, A. da Silva, 2004. The Architecture of the Earth System Modeling Framework. *Computing in Science and Engineering*, 6, 18-28.

Hollinger, J.P., 1991. DMSP Special Sensor Microwave/Imager Calibration/Validation – Final Report Volume II', Naval Research Laboratory, Washington, DC.

Hunke, E.C. and W.H. Lipscomb, 2004. CICE: the Los Alamos sea ice model documentation and software user's manual. <http://climate.lanl.gov/Models/CICE>

Lebedev, K. V., H. Yoshinari, N. A. Maximenko, and P. W. Hacker (2007), Velocity data assessed from trajectories of Argo floats at parking level and at the sea surface, IPRC Technical Note No. 4(2), Honolulu, 16pp.

Markus, T. and D.J. Cavalieri, 2000. An Enhancement of the NASA Team Sea Ice Algorithm. *IEEE Trans Geoscience Remote Sensing*, vol. 38, pp. 1387-1398, 2000.

Scott, R. B., B. K. Arbic, E. P. Chassignet, A. C. Coward, M. Maltrud, W. J. Merryfield, A. Srinivasan, and A. Varghese (2010), Total kinetic energy in four global eddying ocean circulation models and over 5000 current meter records, *Ocean Modell.*, 32, 157-169.

Warn-Varnas, A.C., S.A. Chin-Bing, D.B. King, Z. Hallock, and J.A. Hawkins, 2003. Ocean-acoustic solitary wave studies and predictions. *Surveys in Geophysics*, 24, 39-79.

Warn-Varnas, A.C., S.A. Chin-Bing, D.B. King, J.A. Hawkins, K.G. Lamb, and J.F. Lynch, 2007. Winter PRIMER ocean-acoustic solitary wave modeling studies. *IEEE J. Oceanic Engineering*, 32(2), 436-452.

PUBLICATIONS

Adams, D. K., D. J. McGillicuddy Jr., L. Zamudio, A. M. Thurnherr, X. Liang, O. Rouxel, C. R. German, L. S. Mullineaux (2011), Surface-generated mesoscale eddies transport deep-sea products from hydrothermal vents. *Science* 332, 580 (2011); DOI: 10.1126/science.1201066. [published, refereed]

Arbic, B.K., K.L. Polzin, R.B. Scott, J.G. Richman, and J.F. Shriver, 2011: On Eddy Viscosity, Energy Cascades, and the Horizontal Resolution of Gridded Satellite Altimeter Products. *Journal of Physical Oceanography* [refereed]

Arbic, B.K., R.B. Scott, D.B. Chelton, J.G. Richman, and J.F. Shriver, 2011: Effects of Stencil Width on Ocean Surface Geostrophic Velocity and Vorticity Estimation from Gridded Satellite Altimeter Data, *Journal of Geophysical Research* [refereed]

Arbic, B.K., R.B. Scott, G.F. Flierl, J.G. Richman and J.F. Shriver, 2011: Nonlinear Cascades of Surface Oceanic Geostrophic Kinetic Energy in the Frequency Domain, *Journal of Physical Oceanography* [refereed]

González-Rodríguez, E., Trasviñastro, A., Gaxiola-Castro, G., Zamudio, L., and Cervantes-Duarte, R. Net primary productivity, upwelling and coastal currents in the Gulf of Ulloa, Baja California, Mexico, *Ocean Sci. Discuss.*, 8, 1979-1999, doi:10.5194/osd-8-1979-2011, 2011. [published as a discussion paper, refereed]

Hebert, D.A., J.A. Cummings, E.J. Metzger, P.G. Posey, R.H. Preller, A.J. Wallcraft, M.W. Phelps, and O.M. Smedstad, 2011: Improving Arctic Forecasts by Assimilating High Resolution, Near Real Time Ice Concentration, G. R. L. [refereed].

Hurlburt, H.E., E.J. Metzger, J.G. Richman, E.P. Chassignet, Y. Drillet, M.W. Hecht, O. Le Galloudec, J.F. Shriver, X. Xu, and L. Zamudio, 2011: Dynamical evaluation of ocean models using the Gulf Stream as an example. in *Operational Oceanography in the 21st Century*, Brassington, G. B., and Schiller, A., eds., Springer-Verlag, New York, pp. 545-609R [published].

Jia, Y., P.H.R. Calil, E.P. Chassignet, E.J. Metzger, J.T. Potemra, K.J. Richards, and A. J. Wallcraft, 2011: Generation of mesoscale eddies in the lee of the Hawaiian Islands, *J.G.R. Oceans* [in press, refereed].

Joseph, S., A.J. Wallcraft, T.G. Jensen, M. Ravichandran, S.S.C. Shenoi, and S. Nayak, 2011: Weakening of Spring Wyrtki jets in Indian Ocean, *J.G.R. Oceans* [refereed].

Metzger, E.J., H.E. Hurlburt, A.J. Wallcraft, J.F. Shriver, T.L. Townsend, O.M. Smedstad, P.G. Thoppil, D.S. Franklin and G. Peggion, 2010: Validation Test Report for the Global Ocean Prediction System v3.0 - 1/12° HYCOM/NCODA: Phase II, NRL Report NRL/MR/7320—10-9236. [published]

Pal, R., J.G. Richman and A.J. Wallcraft, 2011: Modeling the Surface Mixed Layer: A Case Study at the Hawaii Ocean Time-series Station, *J. Marine Systems* [refereed].

Posey, P.G., D.A. Hebert, E.J. Metzger, A.J. Wallcraft, J.A Cummings and R.H. Preller, O.M. Smedstad, and M.W. Phelps, 2011: Real-time Data Assimilation of Satellite Derived Ice Concentration into the Arctic Cap Nowcast/Forecast System (ACNFS), *OCEANS 11* Kona, HI [published].

Posey, P.G. E.J. Metzger, A.J. Wallcraft, R.H. Preller, O.M. Smedstad and M.W. PhelpsS, 2010: Validation of the 1/12° Arctic Cap Nowcast/Forecast System (ACNFS), NRL Memorandum Report #9287 [published].

Richman, J.G., H.E. Hurlburt, H.E. Hurlburt, E.J. Metzger J.F. Shriver, A.J. Wallcraft and O.M. Smedstad, 2010: Impact of data assimilation and resolution on modeling the Gulf Stream pathway, Proceedings of the 2010 HPCMP User's Group Conference, Schaumburg, IL. [published]

Richman, J.G. and A.J. Wallcraft, 2011: Impact of Internal Waves on the Wavenumber Spectra of Sea Surface Height and Kinetic Energy, G. R. L. [refereed].

Shinoda, T., W. Han, E.J. Metzger, H.E. Hurlburt, 2011: Seasonal Variation of the Indonesian Throughflow., J. Phys. Oceanogr., [refereed].

Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft and P.G. Timko, 2011: Comparison of Internal Tides in a High Resolution Global Ocean Circulation Model with Altimetric Estimates, G. R. L. [refereed].

Thoppil, P.G., J.G. Richman and P.J. Hogan, 2011: Energetics of a Global Ocean Circulation Model Compared to Observations, Geophysical Research Letters, [published, refereed]

Timko P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger and A.J. Wallcraft, 2011: Comparison of tidal kinetic energy in a global three-dimensional circulation model, historical current meter observations, and a global barotropic model, J. G. R. Oceans [refereed].

Timko P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger and A.J. Wallcraft, 2011: Skill tests of three-dimensional tidal currents in a global ocean model: A look at the North Atlantic, J. G. R. Oceans [refereed].

TrasviñA., K. J. Heywood, A. H. H. Renner, S.E. Thorpe, A.F. Thompson, and L. Zamudio, 2011: The impact of high frequency currents on dispersion off the eastern Antarctic Peninsula. J. Geophys. Res. [in press, refereed]

Zamudio, L., E. J. Metzger, and P. J. Hogan, 2011: Modeling the seasonal and interannual variability of the Northern Gulf of California salinity. J. Geophys. Res., 116, C02017, doi:10.1029/2010JC006631. [published, refereed]